The Quality of Complex Systems and Industry Structure

by

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Abstract

The structure of the telecommunications industry has changed substantially in the last decade, raising public concern that the quality of our information infrastructure may be adversely affected. This paper extends the standard vertical differentiation model of imperfect competition to address the case of the choice of quality in complex systems. In these systems each demanded good consists of two complementary components whose quality may be set by competing firms. The extended framework is used to examine how changes in the vertical and horizontal structure of the industry affect the choice of compatibility, the overall system quality, the equilibrium market prices, and the allocation of surplus. The results from this analysis are interpreted in light of changes in the structure of the telecommunications industry.

The Quality of Complex Systems and Industry Structure

1. Introduction

Most products may be thought of as complex systems, or ***networks***, composed of sub-systems and components. This is especially true of many information technology products. Networks may be physical, as in the case of the telephone, cable television or Internet communication networks; or they may be logical, as in the case of the different software modules/layers which must interact to support an application such as word processing, electronic mail or customer billing.[1] The quality of these networks depends on the quality of the constituent sub-systems. For example, the clarity of a long distance call depends on the qualities of the telephone sets on both ends, the originating and terminating local exchange networks and the long distance carrier's network. Coordinating design and investment decisions to assure appropriate quality-of-service levels is difficult enough when all of the components are owned by the same company. What happens when different firms own different parts of the network? Should we be concerned that changes in industry structure will lead to reductions in the quality of our information infrastructure?

To answer these questions, we develop a model of quality competition with complementary components. Each firm produces either or both of two components which must be combined to create a usable system. For example, the components may include local access and long distance, computer hardware and software, or a stereo receiver and speakers. We examine how changes in industry structure affect firms' pricing and product-design behavior. Although subject to important caveats, this analysis yields four results which should be of interest to policy-makers.

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[1] For a comprehensive discussion of the economics of networks see Economides and White (1994).

First, ***network quality and total surplus are higher and prices are lower when there exists a vertically integrated firm offering a complete system***. This suggests that the re-integration of local and long distance carriers may improve total welfare and incentives to invest in higher quality telecommunications infrastructure.

Second, ***effective competition is not sustainable in the face of a bottleneck facility, even if interconnection is required, unless regulations also control the price of access to the bottleneck***. The introduction of quality competition provides another strategic variable which can be manipulated by the owner of the bottleneck facility to foreclose downstream competition.[2]

Third, ***competition among integrated producers improves total welfare, leading to lower prices, a larger total market and increased quality/variety available***. This suggests that there will be a social benefit from having multiple ***integrated*** carriers offering long distance, cable television and other information technology services.[3]

Fourth, ***once we have two integrated producers competing, there are no gains from requiring interconnection***. The firms will behave so as to deny demand to hybrid system markets (i.e., systems which are composed of components from two or more firms). Thus, introducing quality as a decision variable, reverses the results of Matutes and Regibeau (1988, 1992) and Economides (1988, 1989, 1991) that vertically integrated producers will choose to interconnect their sub-networks so as to offer hybrid systems.

Four features should be considered when interpreting the results of this paper. First, we assume consumers differ only with respect to their willingness-to-pay for improvements in quality

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[2] Moreover, the quality of the bottleneck facility sets the maximum system quality which will be available to consumers. This last point follows directly from our modelling assumption that the quality of a system is never higher than the quality of the weakest link in the system.

[3] Although the simplified approach towards costs in the present analysis precludes determining whether such competition is feasible (e.g., whether local access services are a natural monopoly), it helps alleviate our concern regarding the strategic impact of competition on infrastructure quality.

beyond a minimum quality level. Consumers rank all products identically according to a uni-dimensional quality index.[4]

Second, if firms choose to produce identical quality products, then these products will be perceived by consumers as perfect substitutes and competition will result in marginal cost pricing. To avoid this, firms will choose to quality-differentiate if they choose to offer products of higher than the minimum quality.

Third, firms cannot price discriminate among consumers except by manipulating component versus system prices (i.e., product bundling) and by offering multiple quality levels. This precludes complex price discrimination strategies such as two-part pricing or volume discounting (e.g., WATs services).

Fourth, we ignore positive demand externalities (network externalities) that do not arise as part of the particular mix and match structure that we examine.[5] For example, a telecommunications network exhibits network externalities if consumers typically are willing to pay more to join a larger network because they have more options of who to call; similarly consumers may prefer to purchase the more popular hardware platform because more software is available. Our model excludes network externalities that arise ***outside*** the model. However, interconnection and compatibility which are analyzed in the model may increase the demand of some components, and this may be considered a network externality. The effect on quality equilibria of including positive externalities that arise outside our model is ambiguous. It could either increase or decrease network quality, depending on how customer markets are served. Addressing this issue is an important topic for future research.

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[4] The present analysis is inappropriate when such a ranking is impossible. This may occur if consumers measure quality along multiple dimensions which are not mappable into a unitary index (e.g., they view a comparison of reliability and customer service as akin to comparing "apples and oranges").

[5] See for example Besen and Johnson (1986), David and Greenstein (1990), Economides and White (1994), Farrell and Saloner (1985, 1986), and Katz and Shapiro (1986).

The rest of this paper is organized into four sections. Section 2 describes our model, its relationship to other models in the literature and our solution approach. We proceed by analyzing how changes in industry structure alter equilibrium solutions in a number of cases. These cases were chosen both to isolate the effects of specific changes in the regulatory and/or market environment and to correspond to real world situations where network quality is an issue. The cases are distinguished by (1) the number of firms, (2) the degree of vertical integration of each of the firms, (3) whether firms are allowed to price discriminate, and, (4) whether integrated firms' components are compatible (i.e., are hybrid systems available?). Section 3 derives the results by applying the approach outlined in Section 2 to each of the cases summarized in Figure 1. Readers who are more interested in the interpretation of these results may skip this section. Section 4 interprets our cases in light of the real world, summarizes our four principal conclusions and suggests opportunities for future research.

2. The Model Set-up

There is a rich literature that analyzes imperfect competition when firms use quality to differentiate their products.[6] Traditional models focus on a market for a single product which is available at different quality levels. There is a continuum of consumer types who rank the products identically, but differ in their willingness-to-pay for quality. For example, a representative consumer of type θ who buys one unit of a product of quality q at price p receives utility

$$U_\theta(q, p) = \theta q - p, \tag{1}$$

or, if the consumer chooses not to purchase a good, she receives her reference utility U_θ^0 which is normalized to zero. When coupled with an assumption regarding the distribution of consumer

[6] Gabszewicz and Thisse (1979, 1980), Mussa and Rosen (1978), Shaked and Sutton (1982) among others.

types, these preferences allow one to compute the demand for each product quality level. For example, it is common in the literature to assume that consumer types are distributed uniformly on the unit interval, or

$$\theta \sim \text{Uniformly on } [0, 1]. \tag{2}$$

Then in a market with a single product of quality q, all consumers of types $\theta \geq p/q$ will purchase the product thus yielding a demand of $1 - (p/q)$.

Following Hotelling (1929) and Shaked and Sutton (1982), we model the firms as competing in a two-stage game. In the first stage, the firms choose quality specifications for their products, and in the second stage they choose prices (see Figure 2).[7] In the second stage, price competition leads to zero prices whenever both firms' products are perfect substitutes (i.e., have identical quality levels). Firms which produce products of different quality may charge different prices in equilibrium and divide the market. For example, let one firm offers a high quality product of quality q_H at price p_H and the other firm offers a low quality product of quality q_L and price p_L. Then there will be a marginal consumer with type θ_{L0} who is indifferent between purchasing the low quality product and no product,

$$\theta_{L0} = p_L/q_L \in [0, 1], \tag{3}$$

and another consumer with type θ_{HL} who is indifferent between purchasing the high or low quality product,

$$\theta_{HL} = (p_H - p_L)/(q_H - q_L) \in [\theta_{L0}, 1]. \tag{4}$$

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[7] As is typical, we assume perfect information and symmetric production technologies. Consumers know the prices and qualities of all available products when they make their purchase decisions and firms agree on the nature of consumer demand and the structure of the strategic game they are playing. Symmetric production technologies assure that the firms costs are similar which focuses attention on their strategic behavior with respect to product design and pricing.

Demand for the high quality product will be $1 - \theta_{HL}$ and demand for the low quality product will be $\theta_{HL} - \theta_{L0}$.[8] Non-cooperative equilibrium prices levels $p_1^*(q_1, q_2)$, $p_2^*(q_1, q_2)$, are determined in the second stage game as solutions to $\partial\Pi_1(p_1, p_2, q_1, q_2)/\partial p_1 = \partial\Pi_2(p_1, p_2, q_1, q_2)/\partial p_2 = 0$. Equilibrium quality levels are found in the first stage of the game as solutions of $d\Pi_1(p_1^*(q_1, q_2), p_2^*(q_1, q_2), q_1, q_2)/dq_1 = d\Pi_2(p_1^*(q_1, q_2), p_2^*(q_1, q_2), q_1, q_2)/dq_2 = 0$.

This framework is useful for analyzing the determination of equilibrium qualities and prices. It can also be used to determine how changes in industry structure (e.g., entry/exit) affect firms' product design (i.e., quality choices) and pricing behavior in equilibrium. We extend this basic framework of vertical product differentiation by assuming that each demanded composite good (or system) consists of a network of two components, A and B, with qualities q_A and q_B. Consumer preferences are defined with respect to the quality of the composite good, q_{AB}, which is equal to the minimum of the component qualities:

$$U_\theta(q_{AB}, p_{AB}) = \theta q_{AB} - p_{AB} \tag{5}$$

where,

$$q_{AB} = \min(q_A, q_B) \in [0,\infty) \text{ and } U_\theta(0, p_{AB}) = 0 \tag{6}$$

and p_{AB} is the price which the consumer pays for the composite good or system.

If firms' components are ***compatible***, then it is possible to create a ***hybrid system*** by combining the A component from one firm with the B component from another firm. The price for this system is equal to the sum of the individual component prices. If a firm is allowed to ***price discriminate*** then it may charge a price for a bundled system (composed of two components from the same firm) which is different than the sum of the firm's individual

[8] p_L must be less than p_H or the demand for the low quality product will be zero.

component prices.[9] The regulatory policy known as Open Network Architecture (ONA) prohibits this form of price discrimination. ONA requires common carriers to offer component pricing (and hence interconnection via compatible components) which does not discriminate between hybrid and bundled systems.

We assume that there is an increasing, convex fixed cost associated with improving quality above the minimal level, but that marginal costs are zero.[10] Specifically, we assume that the cost to a firm of providing component i of quality q_i is

$$C(q_i) = q_i^2/4, \quad \text{where } i = A, B. \tag{7}$$

A firm's total costs are computed as the sum of the component costs for each component produced by the firm. Thus, ***there are scale economies associated with quality but no scope economies from vertical integration***.

A strategy for a firm which produces n components is a choice of qualities for each of the components in the first stage and a set of prices for each of the components in the second stage, conditional on ***all*** of the firms' quality choices from the first stage. A solution to this game consists of a set of equilibrium quality and pricing decisions for each firm. We focus on subgame perfect Nash equilibria.[11]

For each of the industry structures described in Figure 1, we determine price-quality equilibria. The game structure is pictured in Figure 2. In each case, we begin by specifying (1)

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[9] They may also charge different component prices based on the identity of the firm supplying the complementary component if there is more than one.

[10] This latter assumption could be relaxed if we re-interpret prices as increments above a constant positive marginal cost.

[11] At equilibrium, no firm can increase its profits by altering its behavior unilaterally, given that the other firms are playing their Nash strategies. Subgame-perfection ensures that the equilibrium is appropriately decentralizable in any subgame.

the number of firms and the components each produces, (2) whether price discrimination is allowed, and (3) whether the firms' components are compatible (or interconnected). This determines the range of system products which will be available to consumers. The game is solved recursively, starting with the competitive pricing equilibrium in the second stage. In order to obtain a pricing equilibrium when there are multiple products, we need to assume an ordering of component qualities.[12] If a pricing equilibrium does not exist, then the assumed ordering of product qualities is not part of a subgame perfect Nash equilibrium. If we find a pricing equilibrium, then we substitute this into the firms' profit functions and solve for a quality equilibrium for the first stage. A solution to the game, if it exists, is a set of product qualities and prices which can be used to compute the share of the market served, firm profits and consumer surplus. Since a firm can always choose to set the quality of every component equal to zero, profits should always be weakly positive. We can interpret a firm earning zero profits as inactive in the market. The threat of entry does not constrain the behavior of active firms because these markets are not contestable (Baumol, Panzar and Willig, 1982).[13] This procedure is followed for each possible ordering of component qualities and for each of the candidate industry structures identified in Figure 1.[14]

[12] The ordering of component qualities will define an ordering for product qualities. For example (see Section 3.5.2), with two firms each producing an upstream and downstream product which are compatible, there are four system products and over 4!=24 possible orderings for the component qualities. Once we know the ordering of product qualities we can infer consumer demand as a function of prices and qualities and can write down the firms' profit functions. The First Order Necessary Conditions (FONCs) obtained when profits are differentiated with respect to prices identify the pure strategy equilibrium for the second stage.

[13] To be active a firm must offer a component with positive quality. Since this incurs a fixed entry cost which is sunk in the second stage, there is not free entry in the pricing game. This precludes "hit-and-run" entry which, in any case, seems unlikely in telecommunications.

[14] We ignore cases which are only the mirror image of one already considered and dispense with trivial cases in a sentence or two.

3. Analysis of the Model

This section derives the quality and pricing equilibria for each of the cases summarized in Figure 1. Readers who are not interested in the mathematical derivation of the results, may proceed directly to discussion in Section 4. The results are summarized in Figures 3 and 4.

3.1.1 Vertically Integrated Monopolist

We first consider a vertically integrated monopolist who produces a single version of each component, A and B, and sells them as a single product AB. Since consumers care only about the quality of the composite good, AB, their willingness-to-pay depends on the minimum of q_A and q_B. Since there is never a revenue gain associated with increasing a component's quality above the highest quality component with which it might be paired and since component costs increase with quality, we should expect the highest quality upstream and downstream components to have the same quality in *all* equilibria. Therefore, the monopolist will choose identical component qualities $q = q_A = q_B$.

Since the monopolist sells a single composite good, price discrimination based on quality is impossible. Hence, the monopolist will quote a single bundled price, p, for the good AB. The marginal consumer, θ_1, who is indifferent between buying or not buying AB, is defined by

$$\theta_1 q - p = 0 \iff \theta_1 = p/q \tag{8}$$

All consumers of types $\theta \in [\theta_1, 1]$ will purchase the good; thus the monopolist's profits are:

$$\Pi_1(p, q) = p(1 - \theta_1) - 2(1/4)q^2 = p - p^2/q - q^2/2. \tag{9}$$

These profits are maximized when the monopolist sets her price at $p^*(q) = q/2$. This implies that at the first stage, the monopolist will choose quality q to maximize

$$\Pi_1(p^*(q), q) = q/4 - q^2/2. \tag{10}$$

The optimal choice for q^* is 1/4. This implies that $p^* = 1/8$, $\theta_1 = 1/2$ and $\Pi(p^*, q^*) = 1/32$. Consumer surplus in this case is also 1/32.[15]

3.1.2 Multiproduct Vertically Integrated Monopolist

The above analysis considered the case of a single product monopolist. We show below that, given our demand and cost assumptions, ***the monopolist will not choose to introduce a second product quality***. To see this, consider the situation where the monopolist offers a high quality upstream/downstream product of quality q_1 and price p_1, and a second lower-quality downstream component of quality q_2 and price p_2. In this case, demands for the high and low quality systems are $1 - \theta_1$ and $\theta_1 - \theta_2$ respectively, where $\theta_1 = (p_1 - p_2)/(q_1 - q_2)$ and $\theta_2 = p_2/q_2$. The firm's profits are

$$\Pi_1(p, q) = p_1(1 - \theta_1) + p_2(\theta_1 - \theta_2) - q_1^2/2 - q_2^2/4 \qquad (11)$$

which implies that the optimal second stage prices are $p_1^* = q_1/2$ and $p_2^* = q_2/2$.[16] At these prices, the monopolist's profits are

$$\Pi_1(p^*(q), q) = q_1/4 - q_1^2/2 - q_2^2/4. \qquad (12)$$

To maximize these profits, the monopolist should set the quality of the low quality product equal to zero, $q_2 = 0$. Then the optimal quality of the high quality product is equal to 1/4, as before. A zero quality product is identical to the outside good. Therefore, the integrated monopolist will choose not to offer a second quality-differentiated product.

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15 Integrating consumer surplus of individual types $U_\theta(q^*, p^*) = \theta q^* - p^*$ over $[\theta_1, 1]$ we get $½(1 - \theta_1^2)q^* - (1 - \theta_1)p^* = 1/32 = 0.03125$.

16 Substituting for θ_1 and θ_2 and differentiating (11) with respect to p_1 and p_2 respectively yields the following two FONCs: $((q_1 - q_2) - 2(p_1 - p_2))/(q_1 - q_2) = 0$ and $2(q_2p_1 - q_1p_2)/(q_2(q_1 - q_2)) = 0$. Solving these for p_1 and p_2 yields the indicated solution.

3.1.3 Socially Optimal Solution

Before analyzing other industry structures, it is worthwhile computing the socially optimal solution with a single product under a break-even constraint and no price discrimination. This is obtained by maximizing consumer surplus subject to the constraint that the firm recovers its costs. The maximization problem to be solved is as follows:

$$\max_{\theta_1} \left[\int_{\theta_1}^{1} (q\theta - p)d\theta\right] \qquad (13a)$$

subject to:

$$\Pi(q, p) = 0 = p(1 - \theta_1) - \frac{1}{2}q^2 \qquad (13b)$$

and

$$q\theta_1 - p = 0 \qquad (13c)$$

Equation (13a) defines total consumer surplus which is equal to total surplus when firm profits are constrained equal to zero, as in constraint (13b). Constraint (13c) identifies the marginal consumer with type θ_1. Solving (13b) and (13c) for p and q as functions of θ_1 yields $p = 2\theta_1^2(1 - \theta_1)$ and $q = 2\theta_1(1 - \theta_1)$. After substituting for p and q in (13a), the optimal θ_1^* is 1/4, which implies that $p^* = (6/64) \simeq 0.094$, $q^* = (3/8) = 0.375$, and total surplus is 0.1055. This is the outcome which maximizes total surplus if the firm is constrained to uniform pricing and to offering a single product.

If the firm could perfectly price discriminate in order to recover its costs, then the maximization problem which would define the optimal solution would be:

$$\max_{q} \left[\int_{0}^{1} (q\theta)\, d\theta \; - \; \frac{1}{2} q^{2} \right] \tag{14}$$

Under perfect price discrimination, there is no reason not to serve the entire market and allow all consumers to enjoy the highest quality product. Therefore, the marginal consumer θ_1^{**} will have type zero, will be charged a zero price; there would be no reason to offer a second, lower quality product.[17] Higher type consumers will pay higher prices. Total surplus is maximized at $q^{**} = 1/4$; this results in total surplus of (1/8). In principle, this could be distributed between the firm and consumers via lump sum transfers according to whatever allocation seemed desirable.

A comparison of this solution and the single product/uniform pricing solution highlights the important role which quality-differentiated product lines may play in implementing second degree price discrimination. It is common for a firm to offer multiple products which are designed and priced in order to induce customers to self-select so that consumers with a high willingness-to-pay choose to purchase more expensive products.[18] There is a large literature discussing the design of optimal tariffs to implement this type of second degree price discrimination which may be based on quality differentiation, volume of purchases or some other observable attribute which allows customers to be segregated into self-selected groups. Mitchell

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[17] Since costs do not increase but total surplus does increase when demand increases, it is efficient to price discriminate so that everyone consumes the highest quality product. Since no one would consume lower quality products, these should not be produced.

[18] From Section 3.1.2, we know that the monopolist does not find this profitable in our model. We did not compute the socially optimal solution under uniform pricing with multiple products because the incremental gains over the single product uniform case would be small (i.e., the socially optimal single product/uniform pricing solution already produces surplus equal to 84% of the level achieved with perfect price discrimination.)

and Vogelsang (1991) offer an introduction to this literature and its application to telecommunications.

These two solutions provide benchmarks against which to compare the outcomes under alternative industry structures. For example, in the absence of perfect price discrimination, the monopolist sets lower quality (0.25 instead of 0.375), higher prices (0.125 instead of 0.094) and serves a smaller share of the market (50% instead of 75%), which yields only 59% as much total surplus (0.0625 instead of 0.1055).

3.2 Bilateral Monopoly: Independent (Non-Integrated) Monopolists Upstream and Downstream

Consider now the case when each component is produced by a different independent monopolist. The upstream monopolist produces A and the downstream monopolist produces B. They are sold at prices p_A and p_B respectively, so that the composite good AB is available at price $p = p_A + p_B$. By the same reasoning as above, both the upstream and downstream monopolists will choose to set identical qualities. Therefore, the composite good has quality $q = q_A = q_B$. All consumers with marginal willingness to pay for quality larger than $\theta_1 = p/q$ purchase the good. Profits for the two firms are:

$$\Pi_A(p, q) = p_A(1 - \theta_1) - q^2/4 \quad \text{and} \quad \Pi_B(p, q) = p_B(1 - \theta_1) - q^2/4. \tag{15}$$

Solving the First Order Necessary Conditions (FONCs) for profit maximization for the second stage, $\partial\Pi_1/\partial p_A = 0$ and $\partial\Pi_2/\partial p_B = 0$, yields equilibrium prices $p_A^*(q) = p_B^*(q) = q/3$, and $p^*(q) = 2q/3$.[19] When compared to the earlier case of a single integrated monopolist, prices here are higher for any level of quality. This is because of the double marginalization effects first

[19] This symmetric pricing equilibrium is the unique Bertrand pricing equilibrium.

observed by Cournot (1838). Essentially, each of the independent monopolists is unable to appropriate the full benefits of a decrease in its own price.[20]

Anticipating these equilibrium prices, each firm chooses in the first stage the quality of its component so as to maximize its profits:

$$\Pi_1(p^*(q), q) = \Pi_2(p^*(q), q) = q/9 - q^2/4. \tag{16}$$

The non-cooperative equilibrium choice for each firm is to set $q^* = 2/9$, which implies that $p^* = 4/27$, $\theta_1 = 2/3$, and $\Pi_1(p^*, q^*) = \Pi_2(p^*, q^*) = 1/81$. Consumer surplus in this case is also 1/81 ($\simeq$ 0.0123).

Compared to the case of integrated monopoly, because of double marginalization, in bilateral monopoly marginal increases in quality have a bigger impact on price. Being able to sell the same quality at a higher price than under integrated monopoly, the bilateral monopolists choose lower quality levels, which are less costly. Despite that, because of double marginalization, prices are higher than in integrated monopoly, a lower portion of the market is served, and firms realize lower profits. Consumers also receive lower surplus in comparison to vertically integrated monopoly. The effects of the lack of vertical integration on price are known. The interesting result here is that ***lack of vertical integration (unbundling) leads to a reduction in quality***. Note that this is not because of lack of coordination between the bilateral monopolists in the choice of quality, since they both choose the same quality level.

3.3 Integrated Firm Facing Competition in One Component

We now consider a duopoly where firm 1 provides end-to-end service, while firm 2 produces only the downstream component. Here, there are two possibilities we must consider: (1) firm 1 produces two complementary components (A_1 and B_1) of equal quality, while firm

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[20] See Economides and Salop (1992) for a discussion of the effects of double marginalization of vertical mergers under compatibility.

2 produces product B_2 of lower quality; or, (2) firm 1 produces a high quality A_1 and a low quality B_1, while firm 2 produces a high quality B_2.[21] For each of these cases, there are two additional sub-cases depending on whether we allow firm 1 to price discriminate with respect to the price of A_1 depending on whether it is bundled with B_1 or B_2.

3.3.1 Integrated Firm Produces Components of the Same Quality

We first consider the case when both of the components (A_1 and B_1) that are produced by the integrated firm are of the same quality q_1, and are sold at prices w_1 and v_1 respectively. Firm 2 produces good B_2 of quality q_2 and sells it at price v_2. Since demand for Firm 2's good will depend on the $\min(q_1, q_2)$, firm 2 will always choose $q_2 \leq q_1$.

Now, if firm 1 may price discriminate, it can always set the price of w_1 to hybrid system purchasers sufficiently high to foreclose firm 2 from the market. Since monopoly profits are higher with a single product (as we have shown earlier), firm 1 will choose to foreclose firm 2 and act as a monopolist (as in section 3.1) if it is allowed to price discriminate.

If firm 1 is prevented from price discriminating, then we need to examine two cases. First, if $q_2 = q_1$, the two systems are perfect substitutes and all of the sales will go to the system with the lower downstream component price, $\min(v_1, v_2)$). At the pricing stage, this will lead to marginal cost pricing for the downstream components, or $v_1 = v_2 = 0$ which will imply negative profits for firm 2 for any $q_2 > 0$. Therefore, if firm 2 is to compete, it must choose $q_2 < q_1$ and $v_2 < v_1$.

With this ordering of qualities, demand for A_1B_1 is $1 - \theta_1$ and demand for A_1B_2 is $\theta_1 - \theta_2$, where $\theta_1 = (v_1 - v_2)/(q_1 - q_2)$ and $\theta_2 = (w_1 + v_2)/q_2$. The firms' profits are:

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[21] The other possibilities are not viable. If all three qualities are equal then the composite goods have the same quality which leads to marginal cost pricing and is not an equilibrium. If the upstream component A_1 is low quality, then again, the composite goods will have the same (low) quality.

$$\Pi_1 = w_1(1 - \theta_2) + v_1(1 - \theta_1) - q_1^2/2 \quad \text{and} \quad \Pi_2 = v_2(\theta_1 - \theta_2) - q_2^2/4 \tag{17}$$

The price equilibrium in the last stage is[22] $w_1^* = q_2/2$, $v_1^* = (q_1 - q_2)/2$, and $v_2^* = 0$. Therefore, even if firm 1 is prohibited from price discriminating, firm 1 will price at the second stage so as to foreclose firm 2 from the market. Anticipating this, the second firm would set its quality $q_2^* = 0$ and the first firm would behave as a single product monopolist (Section 3.1).

3.3.2 Integrated Firm Produces Components of Different Qualities

We now consider the case where the components of firm 1 (A_1 and B_1) are of different qualities q_{A1} and q_{B1} respectively. Obviously, the bottleneck upstream component must have the higher quality (i.e., $q_{A1} > q_{B1}$). For it to be rational for firm 1 to produce an upstream component of higher quality, the quality of firm 2's component, B_2, must be higher than the quality of B_1 (i.e., $q_{B2} > q_{B1}$). Since there is no gain to either firm from producing higher-than-necessary quality, $q_{A1} = q_{B2} = q_1 > q_{B1} = q_2$.

In the absence of price discrimination, let the prices for A_1, B_1 and B_2 be w_1, v_1 and v_2 respectively. Thus, there is a high quality hybrid system A_1B_2 with quality q_1 sold at price $w_1 + v_2$, and a low quality bundled system A_1B_1 with quality q_2 sold at price $w_1 + v_1$. The demands for A_1B_2 and A_1B_1 are $1 - \theta_1$ and $\theta_1 - \theta_2$ respectively, where $\theta_1 = (v_2 - v_1)/(q_1 - q_2)$ and $\theta_2 = (w_1 + v_1)/q_2$. The profit functions are:

$$\begin{aligned} \Pi_1 &= w_1(1 - \theta_2) + v_1(\theta_1 - \theta_2) - q_1^2/4 - q_2^2/4 \\ \Pi_2 &= v_2(1 - \theta_1) - q_1^2/4. \end{aligned} \tag{18}$$

[22] First order conditions are $0 = \partial\Pi_1/\partial w_1 = 1 - (2w_1 + v_2)/q_2$, $0 = \partial\Pi_1/\partial v_1 = 1 - (2v_1 - v_2)/(q_1 - q_2)$, $0 = \partial\Pi_2/\partial v_2 = (v_1 - 2v_2)/(q_1 - q_2) - (w_1 + 2v_2)/q_2$.

Solving for the equilibrium second stage prices yields[23]

$$w_1^* = (2q_1 + q_2)/6, \;\; v_1^* = (q_2 - q_1)/3, \;\; v_2^* = (q_1 - q_2)/3.$$

This solution implies $v_1^* < 0$, which cannot be an equilibrium. Constraining $v_1^* = 0$ implies $q_2^* = 0$ as the quality choice. Therefore, this case reduces to the case of two non-integrated monopolists (Case 3.2).

If we allowed price discrimination, then the above solution implies equilibrium system prices of $w_1^* + v_1^* = q_2/2$ for A_1B_1 and $w_1^* + v_2^* = (4q_1 - q_2)/6$ for A_1B_2. This implies that $\theta_1 = 2/3$ and $\theta_2 = 1/2$ regardless of the actual qualities chosen. At these prices, firm profits are:

$$\Pi_1(q_1, q_2) = q_1/9 - q_1^2/4 + 5q_2/36 - q_2^2/4 \;\text{ and }\; \Pi_2(q_1, q_2) = (q_1 - q_2)/9 - q_1^2/4. \qquad (19)$$

Solving the first order necessary conditions[24], yields the following equilibrium quality choices: $q_1^* = 2/9$ and $q_2^* = 5/18$, which is impossible under the assumptions of the case. As q_2 approaches q_1, v_2^* goes to zero and firm 2's profits become negative. Therefore, regardless of whether price discrimination is allowed or not, there does not exist a quality equilibrium where the integrated producer has unequal qualities and is competing against a non-integrated competitor. Furthermore, this implies that the case of two non-integrated monopolists discussed in section 3.2 is stable against sequential entry in the form of forward (or backward) integration by either of the incumbents via a quality-differentiated component.

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[23] The FONCs are $\partial\Pi_1/\partial w_1 = (q_1 - 2(w_1 + v_1))/q_2 = 0$, $\partial\Pi_1/\partial v_1 = 2(w_1 + v_1)/q_1 + (2v_1 - v_2)/(q_1 - q_2) = 0$, and $\partial\Pi_2/\partial v_2 = 1 + (v_1 - v_2)/(q_1 - q_2) = 0$.

[24] The FONCs are $\partial\Pi_1/\partial q_1 = \partial\Pi_2/\partial q_1 = 1/9 - q_1/2 = 0$ and $\partial\Pi_1/\partial q_2 = 5/36 - q_2/2 = 0$.

3.4 Each of Three Components Produced by a Different Firm

Now consider the case where there are three firms, each producing a single component. Let firm 1 be the sole producer of the upstream component A_1 and let firms 2 and 3 produce competing versions of the downstream component B_2 and B_3. Let w_1 designate the price of A_1 in the absence of price discrimination; and, when price discrimination is allowed, let w_{12} and w_{13} designate the price of A_1 when bundled with B_2 or B_3, respectively. Let v_2 and v_3 designate the prices of B_2 and B_3.

Once again, a moment's reflection makes it clear that at any equilibrium we must have $q_{A1} = \max(q_{B2}, q_{B3})$, since the first firm will increase its costs but not its revenues if it sets its quality higher than the higher of the two B-component qualities. Without loss of generality, we may assume that $q_1 = q_{A1} = q_{B2} \geq q_{B3}$. This leaves us with two cases to consider: either $q_{B2} = q_{B3}$ or $q_{B2} > q_{B3}$. In the former case, the downstream firms' components are perfect substitutes and hence the equilibrium prices will be zero, implying that $q_{B2} = q_{B3} = 0$. Firm 1's best response is to set $q_{A1} = 0$ and no one will purchase anything.

Assuming $q_1 > q_{B3}$, demand for A_1B_2 is $1 - \theta_1$ and demand for A_1B_3 is $\theta_1 - \theta_2$ where $\theta_1 = (v_2 - v_3)/(q_1 - q_{B3})$ and $\theta_2 = (w_1 + v_3)/q_{B3}$ if price discrimination is prohibited; and $\theta_1 = (w_{12} - w_{13} + v_2 - v_3)/(q_1 - q_{B3})$ and $\theta_2 = (w_{13} + v_3)/q_{B3}$, if price discrimination is allowed. In the absence of price discrimination, the profits are

$$\begin{aligned} \Pi_1 &= w_1(1 - \theta_2) - q_1^2/4 = w_1(1 - (w_1 + v_3)/q_{B3}) - q_1^2/4 \\ \Pi_2 &= v_2(1 - \theta_1) - q_1^2/4 = v_2(1 - (v_2 - v_3)/(q_1 - q_{B3})) - q_1^2/4 \\ \Pi_3 &= v_3(\theta_1 - \theta_2) - q_{B3}^2/4 = v_3((v_2 - v_3)/(q_1 - q_{B3}) - (w_1 + v_3)/q_{B3}) - q_{B3}^2/4 \end{aligned} \tag{20}$$

which implies that the second stage equilibrium prices are $w_1^* = q_{B3}/2$, $v_2^* = (q_1 - q_{B3})/2$ and $v_3^* = 0$.[25] Therefore, the third firm is forced to charge zero price and chooses in the earlier

[25] The FONCs are $\partial\Pi_1/\partial q_1 = (q_{B3} - v_3 - 2w_1)/q_{B3} = 0$, $\partial\Pi_2/\partial q_1 = (q_1 - q_{B3} - 2v_2 + v_3)/(q_1 - q_{B3}) = 0$, and $\partial\Pi_3/\partial q_{B3} = (v_2 q_{B3} - 2v_3 q_1 - w_1(q_1 - q_{B3}))/(q_{B3}(q_1 - q_{B3})) = 0$.

stage to produce a quality of level zero. But, this is equivalent to firm 3 dropping out of the market, since the outside good is of quality level zero. Firms 1 and 2 also anticipate the pricing equilibrium and see that firm 3 is not a threat to them. Thus, at the first stage, firms 1 and 2 choose the quality levels of bilateral monopoly (section 3.2). The price levels of bilateral monopoly follow.[26] This outcome can be thought of as foreclosure of the potential entrant.

If price discrimination is allowed, however, firm 1's profits become

$$\Pi_1 = w_{12}(1 - \theta_1) + w_{13}(\theta_1 - \theta_2) - q_1^2/4 \qquad (21)$$

and the new pricing equilibrium is given by:

$$w_{12}^* = q_1(3q_1 + q_{B3})/(9q_1 - q_{B3}), \;\; w_{13}^* = 4q_1q_{B3}/(9q_1 - q_{B3}),$$
$$v_2^* = 3q_1(q_1 - q_{B3})/(9q_1 - q_{B3}), \;\; v_3^* = q_{B3}(q_1 - q_{B3})/(9q_1 - q_{B3}).$$

These prices yield the following first stage profits:

$$\Pi_1(p^*(q), q) = (9q_1^3 + 7q_1^2q_{B3})/(9q_1 - q_{B3})^2 - q_1^2/4,$$
$$\Pi_2(p^*(q), q) = 9q_1^2(q_1 - q_{B3})/(9q_1 - q_{B3})^2 - q_1^2/4, \qquad (22)$$
$$\Pi_3(p^*(q), q) = q_1q_3(q_1 - q_3)/(9q_1 - q_{B3})^2 - q_{B3}^2/4.$$

Solving the first stage FONC, yields equilibrium qualities of $q_1^* = 2/9 = 0.222$ and $q_{B3}^* = 0.0209$.[27] This implies $\theta_1^* = 0.663$, $\theta_2^* = .551$, $w_{12}^* = 0.0771$, $w_{13}^* = 0.0093$, $v_2^* = 0.06774$, and $v_3^* = 0.0021$. Equilibrium profits are 0.01471, 0.01050 and 0.00013 for firms 1, 2 and 3

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[26] If firms 1 and 2 behave as bilateral monopolists and set their qualities at (2/9) and firm 3 chooses to enter with a quality greater than zero, firms 1 and 2 will price to foreclose firm 3 from the market; thus the bilateral monopoly solution is a Nash equilibrium in the three firm game without price discrimination.

[27] The FONCs are $\partial\Pi_1/\partial q_1 = q_1(162q_1^2 - 729q_1^3 - 54q_1q_{B3} + 243q_1^2q_{B3} - 28q_{B3}^2 - 27q_1q_{B3}^2 + q_{B3}^3)/(2(9q_1 - q_{B3})^3) = 0$, $\partial\Pi_2/\partial q_1 = q_1(162q_1^2 - 729q_1^3 - 54q_1q_{B3} + 243q_1^2q_{B3} + 36q_{B3}^2 - 27q_1q_{B3}^2 + q_{B3}^3)/(2(9q_1 - q_{B3})^3) = 0$, and $\partial\Pi_3/\partial q_{B3} = (18q_1^3 - 34q_1^2q_{B3} - 729q_1^3q_{B3} + 243q_1^2q_{B3}^2 - 27q_1q_{B3}^3 + q_{B3}^4)/(2(9q_1 - q_{B3})^3) = 0$. This system of equations was solved numerically to yield the indicated result.

respectively, and consumer surplus is 0.0136. This case suggests that in order to sustain competition in the downstream component, price discrimination must be allowed.

3.5 Duopoly Competition Between Two Vertically Integrated Firms

In all of the previous cases, the upstream component was a bottleneck facility. The present case considers what happens when we have two integrated firms competing. The discussion of this case is divided into two major sub-sections. In the first subsection, we examine what happens when the components are incompatible so interconnection is not possible and there are no hybrid systems. In the second subsection we assume firms can make their products compatible and interconnection is feasible. In this section we show that firms will price so as to foreclose hybrid systems.

3.5.1 Duopoly Competition of Vertically Integrated Firms with Incompatible Components

In this case, there are two systems available. Firm 1 sells system A_1B_1 of quality q_1 for p_1 and firm 2 sells the system A_2B_2 of quality q_2 for p_2.[28] Without loss of generality, let $q_1 \geq q_2$. Clearly, equal qualities, $q_1 = q_2$, will never be chosen because in the price subgame competition will drive prices to marginal cost. Thus, we confine our attention to the case where q_1 is strictly greater than q_2. Demand for A_1B_1 is $1 - \theta_1$ and demand for A_2B_2 is $\theta_1 - \theta_2$, where $\theta_1 = (p_1 - p_2)/(q_1 - q_2)$ and $\theta_2 = p_2/q_2$. This yields the following profit functions:

$$\Pi_1 = p_1(1 - \theta_1) - q_1^2/2 \quad \text{and} \quad \Pi_2 = p_2(\theta_1 - \theta_2) - q_2^2/2. \tag{23}$$

The second stage pricing equilibrium[29] is

$$p_1^*(q_1, q_2) = 2q_1(q_1 - q_2)/(4q_1 - q_2), \quad p_2^*(q_1, q_2) = q_2(q_1 - q_2)/(4q_1 - q_2).$$

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[28] Once again, it is obvious that $q_1 = q_{A1} = q_{B_1}$ and $q_2 = q_{A_2} = q_{B2}$.

[29] The FONCs are $\partial\Pi_1/\partial p_1 = 0 = 1 - (2p_1 - p_2)/(q_1 - q_2)$ and $\partial\Pi_2/\partial p_2 = 0 = (q_2p_1 - 2q_1p_2)/(q_2(q_1 - q_2))$.

Using these prices to compute the first stage profits and then differentiating profits with respect to quality to get the first order necessary conditions produces a system of fourth order polynomials which do not have an analytic solution.[30] However, these may be solved numerically, yielding the equilibrium qualities $q_1^* = 0.253$ and $q_2^* = 0.048$. These qualities imply $p_1^* = 0.1077$, $p_2^* = 0.0103$, $\theta_1^* = 0.475$, $\theta_2^* = 0.213$. The profits for firm 1 are 0.0244 and for firm 2 are 0.0015. Consumer surplus is 0.0431.

3.5.2 Duopoly Competition of Integrated Firms That Produce Compatible Components

If the two networks discussed above are interconnected, then the hybrid systems A_1B_2 and A_2B_1 may be sold also. This case corresponds to the case where both networks have adopted ***compatible*** technologies so that it is technically feasible to create the hybrid products and the two networks ***are*** interconnected so that the hybrid systems are actually sold. If price discrimination is allowed, either firm can choose to destroy the market for hybrid systems by setting the price for unbundled components suitably high. Therefore, pricing behavior may be used to determine whether components are ***effectively compatible*** (i.e., hybrid systems face non-zero demand in equilibrium).

With four components, there are theoretically over 4!=24 possible quality orders which we should consider; however, a little thought makes it clear that there are really only 3 cases of interest. First, even though there are four component qualities to consider and four systems to choose from (two bundled systems and two hybrid systems), the firms would choose to set the highest qualities of upstream and downstream components equal, so there would never be more

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[30] The FONCs are as follows: $\partial\Pi_1/\partial q_1 = (q_1(16q_1^2 - 64q_1^3 - 12q_1q_2 + 48q_1^2q_2 + 8q_2^2 - 12q_1q_2^2 + q_2^3))/(4q_1 - q_2)^3 = 0$, and $\partial\Pi_2/\partial q_2 = (4q_2^3 - 7q_1^2q_2 - 64q_1^3q_2 + 48q_1^2q_2^2 - 12q_1q_2^3 + q_2^4)/(4q_1 - q_2)^3 = 0$.

than three distinct component qualities in the market place.[31] Without loss of generality we may assume that A_1 is the highest quality component. Letting the qualities of A_1, B_1, A_2 and B_2 be q_{A1}, q_{B1}, q_{A2} and q_{B2}, respectively, we assume $q_{A1} \geq q_{A2}$. Moreover, it is obvious that in any first stage equilibrium, $q_{A1} = \max(q_{B1}, q_{B2})$. This still leaves us with three possible orderings for the component qualities to examine:

(i) $q_{A1} = q_{B1} \geq q_{A2} \geq q_{B2}$ (which is the mirror image of $q_{A1} = q_{B1} \geq q_{B2} \geq q_{A2}$)

(ii) $q_{A1} = q_{A2} \geq q_{B1} \geq q_{B2}$ (which is the mirror image of $q_{A1} = q_{A2} \geq q_{B2} \geq q_{B1}$)

(iii) $q_{A1} = q_{B2} \geq q_{B1} \geq q_{A2}$ (which is the mirror image of $q_{A1} = q_{B2} \geq q_{A2} \geq q_{B1}$)

Each of these cases will be discussed both when price discrimination is allowed and when it is prohibited. If price discrimination is prohibited, let D_{11}, D_{22}, D_{12} and D_{21} designate the demands for the systems A_1B_1, A_2B_2, A_1B_2 and A_2B_1, and let w_1, v_1, w_2 and v_2 designate the prices for A_1, B_1, A_2, B_2. We can write each firms' second stage profit functions as follows:

$$\begin{aligned} \Pi_1 &= w_1(D_{11} + D_{12}) + v_1(D_{11} + D_{21}) - q_{A1}^2/4 - q_{B1}^2/4, \\ \Pi_2 &= w_2(D_{22} + D_{21}) + v_2(D_{22} + D_{12}) - q_{A2}^2/4 - q_{B2}^2/4. \end{aligned} \tag{24}$$

If price discrimination (mixed bundling) is permitted and we let p_1 and p_2 designate the prices for A_1B_1 and A_2B_2, then the profit functions become:

$$\begin{aligned} \Pi_1 &= p_1D_{11} + w_1D_{12} + v_1D_{21} - q_{A1}^2/4 - q_{B1}^2/4, \\ \Pi_2 &= p_2D_{22} + w_2D_{21} + v_2D_{12} - q_{A2}^2/4 - q_{B2}^2/4. \end{aligned} \tag{25}$$

The demand for each system will depend both on the pricing equilibria and on the order of qualities in each of the cases. Let θ_3 designate the consumer who is indifferent between

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[31] It never makes sense to set the quality of a component higher than the quality of the highest quality component with which it may be bundled. Therefore, the highest quality A component and the highest quality B component will have the same quality in any quality equilibrium. If the remaining three components all have different and lower qualities, combining these components yields at most an additional intermediate and low quality system.

purchasing nothing and the minimal quality product available, θ_2 designate the consumer who is indifferent between purchasing the minimal and intermediate quality good, and θ_1 designate the consumer who is indifferent between purchasing the intermediate and the highest quality good. We know that $0 \leq \theta_3 \leq \theta_2 \leq \theta_1 \leq 1$, and that the demand for the highest quality product will be $1 - \theta_1$, the demand for the intermediate quality product will be $\theta_1 - \theta_2$, and the demand for the lowest quality product will be $\theta_2 - \theta_3$. If we find that $\theta_i = \theta_{i+1}$, then demand for the lesser quality of the two systems is zero.

Case 3.5.2(i) $q_{A1} = q_{B1} \geq q_{A2} \geq q_{B2}$

In this case, we have an integrated high quality firm 1 which is competing against a lower quality integrated firm 2. Notice that it cannot be an equilibrium for all of the components to have identical qualities since that would result in zero prices for all components and hence zero qualities. A deviation where one firm produced higher than zero quality would be privately rational and hence all zero qualities would not be an equilibrium. Therefore at least one of the two inequalities must be strict if there is to be an equilibrium with the ordering of component qualities assumed above.

Clearly, the system A_1B_1 has the highest quality and the hybrid system A_2B_1 has either the same or lower, intermediate, quality depending on whether $q_{A1} = q_{B1} = q_{A2}$ or $q_{A1} = q_{B1} > q_{A2}$. If the former were true, then components A_1 and A_2 become perfect substitutes and the only equilibrium price which could prevail would be zero. This cannot be part of a subgame-perfect equilibrium since each firm would prefer to lower the quality of its component of type A and free-ride on its competitor's higher quality component of type A.[32] Therefore, if there is an equilibrium in this case it must be true that the first inequality is strict.

Assuming that both inequalities are strict, the highest quality product is A_1B_1, the intermediate quality good is the hybrid system A_2B_1, and the lowest quality products are A_1B_2 and A_2B_2, which have identical quality, q_{B2}. In the absence of price discrimination, it is obvious that in any quality-price subgame-perfect equilibrium, the price of a higher quality component must be (weakly) higher than the price of a lower quality component.[33] Therefore the price of A_1 must be greater than the price of A_2 and the price of B_1 must be greater than the price of B_2. In these circumstances, the second stage profit functions become

$$\begin{aligned} \Pi_1 &= w_1(D_{11} + D_{12}) + v_1(D_{11} + D_{21}) - q_{A1}^2/4 - q_{B1}^2/4 \\ &= w_1(1 - \theta_1) + v_1(1 - \theta_2) - q_{A1}^2/2 \\ \Pi_2 &= w_2(D_{22} + D_{21}) + v_2(D_{22} + D_{12}) - q_{A1}^2/4 - q_{B2}^2/4 \\ &= w_2(\theta_1 - \theta_2) + v_2(\theta_2 - \theta_3) - q_{A2}^2/4 - q_{B2}^2/4, \end{aligned} \tag{26}$$

where:

$$\theta_1 = (w_1 - w_2)/(q_{A1} - q_{A2}), \quad \theta_2 = (v_1 - v_2)/(q_{A2} - q_{B2}), \quad \theta_3 = (w_2 + v_2)/q_{B2}.$$

The first order necessary conditions associated with the second stage pricing equilibrium imply prices which result in $\theta_1 = \theta_2$, or zero demand for the intermediate quality good in the case

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32 It cannot be an equilibrium for $q_{A1} = q_{A2} = 0$ since this implies $q_{B2} = 0$ which is not an equilibrium as discussed earlier. Therefore, the deviation to lower quality by one firm is always possible. This deviation is privately attractive since the firm's revenues are unaffected while costs decline. Notice that this is true regardless of the pricing equilibrium as long as price discrimination is prohibited.

33 Were this not the case, then the lower quality component would face zero demand. For example if $v_1 < v_2$ then sales of B_2 would be zero. This could not be a pricing equilibrium since firm 2 could deviate to $v_2 = v_1 - \varepsilon$ and capture all of the low quality B market, which would weakly improve firm 2's revenues without affecting its costs. In any profit maximizing equilibrium of the game, the lower quality (lower cost) firm can always pursue such a pricing strategy.

where $q_{A1} = q_{B1} > q_{A2} > q_{B2}$.[34] If this is the pricing equilibrium, then firm 2's revenues are unaffected by setting quality for A_2 higher than B_2, so firm 2 would wish to set $q_{A2} = q_{B2}$. This leaves only one more case to consider, $q_{A1} = q_{B1} > q_{A2} = q_{B2}$.

With this ordering of component qualities, there are only two system qualities available: a high quality system produced by firm 1 and three versions of a low quality system (the two hybrid systems and the bundled system from firm 2). Let $H = w_1 + v_1$ be the equilibrium price for the high quality system and $L = \min(w_1 + v_2, w_2 + v_1, w_2 + v_2)$ be the equilibrium price of the low quality system. Obviously, $H > L$ or we again end up with all zero component qualities which is not an equilibrium.

We now show that with each firm having two prices to set and with zero marginal costs (at the second stage), there is no positive component pricing equilibrium. Without loss of generality, assume $w_2 \leq v_2$. If $q_{A2} > 0$, then $v_2 > 0$. In this case, firm 1 would always prefer to deviate to $v_1^{\dagger} = v_2 - \varepsilon$ and $w_1 = H - v_1^{\dagger}$. However, $v_1 > 0$ and $v_2 = 0$ (implying that $q_{A2} = q_{B2} = 0$), is not an equilibrium since firm 2 would always prefer to deviate to $v_2^{\dagger} = v_1 - \varepsilon$ and $w_2 = L - v_2^{\dagger}$. Finally, $v_1 = v_2$ is not an equilibrium because this again implies $q_{A1} = q_{B1} = q_{A2} = q_{B2} = 0$. Therefore, there is ***no*** pricing equilibrium which can support the above ordering of qualities if price discrimination is prohibited.

In the second stage, the marginal cost of selling a unit of any quality is zero and so neither high quality nor low quality firms can commit to not succumbing to the Bertrand temptation to cut prices to capture additional revenue in the low quality market. Permitting price discrimination would allow the firms to set unbundled prices sufficiently high to prevent

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[34] The FONCs are as follows $\partial\Pi_1/\partial w_1 = 1 - (2w_1 - w_2)/(q_{A1} - q_{A2}) = 0$, $\partial\Pi_1/\partial v_1 = 1 - (2v_1 - v_2)/(q_{A2} - q_{B2}) = 0$, $\partial\Pi_2/\partial w_2 = (2(w_2 + v_2))/q_{B2} + (w_1 - 2w_2)/(q_{A1} - q_{A2}) = 0$, $\partial\Pi_2/\partial v_2 = 0 = 1/q_{B2} + [q_{B2}(2w_2 + v_1) - 2q_{A2}(w_2 + v_2)]/(q_{B2}(q_{A2} - q_{B2}))$. The solution of these FONCs yields the following prices: $w_1 = [(2q_{A1})(q_{A1} - q_{A2})]/\lambda$, $w_2 = [q_{B2}(q_{A1} - q_{A2})]/\lambda$, $v_1 = [2q_{A1}(q_{A2} - q_{B2})]/\lambda$, and $v_2 = [2q_{B2}(q_{A2} - q_{B2})]/\lambda$, where $\lambda = 4q_{A1} - q_{B2}$.

competition from hybrid system products, which would convert this case into the case of competition between vertically integrated duopolists producing incompatible components.

There is no other equilibrium possible with price discrimination since any case where there is an active hybrid system market would have at least two products competing which are perfect substitutes and with three pricing instruments, the equilibrium would be vulnerable to similar deviations to those described above.

Case 3.5.2(ii) $\mathbf{q_{A1} = q_{A2} \geq q_{B1} \geq q_{B2}}$

With this ordering, A_1 and A_2 have identical qualities and by arguments made previously, it is clear the firm 1 would also choose to set the same quality for B_1, which leaves us with only one case to consider: $q_{A1} = q_{B1} = q_{A2} > q_{B2}$. Without price discrimination, we again have the problem of both firms wishing to free-ride on the other firm's quality investment in A_1 which means that this cannot be an equilibrium ordering.

Case 3.5.2(iii) $\mathbf{q_{A1} = q_{B2} \geq q_{B1} \geq q_{A2}}$

Here the highest quality system is the hybrid system A_1B_2, the intermediate quality system is A_1B_1 and the lowest quality system is either A_2B_2 or A_2B_1. Following arguments similar to those above, it is clear that there is no quality/pricing equilibrium with this ordering which faces non-zero demand.

The above discussion makes it clear that there is no equilibrium with positive demand for hybrid system products for any of the possible orderings of component qualities. This seems in contrast with previous results on the choice of compatibility by vertically integrated duopolists. Matutes and Regibeau (1988, 1992) and Economides (1989) have shown that, for symmetric demand systems (when the demands for hybrids are equal to the demand for single-producer composite goods at equal prices), vertically integrated firms prefer compatibility. Economides

(1988, 1991) has shown that this result can be reversed if the demand for hybrids is small relative to the demand of the own system. This is because compatibility increases demand but also increases competition. Thus, a firm that faces a small hybrid demand (relative to the demand of the own system) does not get rewarded sufficiently in terms of demand for the increased competition brought by compatibility and therefore prefers incompatibility. In the model of this paper, the demand for hybrids depends on the quality choices of all four components. Because the quality of a composite good is the minimum of the qualities of its component parts, any quality configuration where the components of each vertically integrated firm have the same quality level but this quality level is different than the common quality of the components of the opponent ($q_{A1} = q_{B1} > q_{A2} = q_{B2}$) will lead both firms to desire incompatibility. In such a case, in the price stage, the hybrid does not give enough demand reward to the low-quality producer, who therefore chooses incompatibility. In a case where an integrated firm produces components of different qualities (e.g., $q_{A1} = q_{B1} > q_{A2} > q_{B2}$), in the pricing stage firms have an incentive to choose compatibility non-cooperatively. However, at the earlier quality stage, the firm that was assumed to produce different qualities has an incentive to equalize its quality levels downward. This move leads the market to the earlier case ($q_{A1} = q_{B1} > q_{A2} = q_{B2}$) where compatibility is not desirable from each firm's point of view. In summary, given certain quality levels, compatibility is desirable as in the previous literature. However, allowing the firms to choose their quality levels drives them toward the market structures where compatibility is undesirable to them.[35] Essentially ***the drive of integrated firms to achieve a uniform quality of all their components while differentiating their quality from that of opponents squeezes out the demand for hybrids and drives firms to incompatibility and lack of interconnection***.

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[35] This open the possibility that allowing firms to endogenously choose their quality or variety levels may reverse the compatibility results of Matutes and Regibeau (1988, 1992) and Economides (1989) in general. This could happen if firms choose variety or quality levels that lead to configurations where the demand for hybrids is small, so that compatibility is undesirable as in Economides (1989, 1991).

4. <u>Implications for the Telecommunications Industry</u>

The history of the Public Switched Telecommunications Network (PSTN) provides a useful vehicle for interpreting the results derived in the preceding sections. As the PSTN evolves into a mixed, hybrid system of public and private facilities, firms' strategic incentives will change. The forces which are altering the PSTN are quite complex. They include technological progress, globalization and deregulation. For example, advances in fiber optics, digital switching and software control are reducing costs and creating new product opportunities. Increased internationalization has encouraged multinational alliances while deregulation is permitting new types of entry. Our model addresses these forces indirectly by examining how changes in the ownership structure of network components and selected regulatory reforms (e.g., ONA pricing and interconnection requirements) change firms' strategic behavior with respect to pricing and product design, which is interpreted as choosing the quality for network services.

The cases summarized in Tables 3 and 4 reflect static equilibria which ignore such important real world issues as multi-part tariffs (i.e., separate fees for access and usage), volume discounting to discriminate between residential and commercial customers (e.g., WATS), and special access or custom-designed virtual private network services. Most importantly, we ignore the effects of rate of return regulation.[36] These omissions are intentional. We believe that telecommunications is moving fast in a completely deregulated environment, and it is this environment that now needs to be studied. Thus, we focus attention on non-cooperative equilibria in prices and quality levels and examined changes in ownership structure, isolated from the possibly distorting influences of technological change, regulatory politics and dynamic investment planning. Therefore, the analogies drawn between the real world situation and the cases are intended to be suggestive rather than exact. However, we believe that our analysis is

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[36] Rate of return regulation may encourage excessive investments in quality if quality improvements are capital intensive (Averch and Johnson, 1962), which seems plausible (e.g., redundant electronics to improve reliability, excess channel capacity to reduce blockage, or additional software features).

closer to the near future state of affairs in telecommunications than an analysis based on regulation would be. With this proviso in mind, let us interpret our results in light of current and prospective changes in the structure of the U.S. telecommunications industry.

The first case we considered (Section 3.1) was the vertically integrated monopolist. This is our base case and corresponds loosely to the pre-divestiture world of AT&T's Bell System, where a single firm provided end-to-end Plain Old Telephone Service (POTS) of a uniform quality as its principal activity. Compared to the socially efficient solution (Section 3.1.3), a monopolist sets higher prices, offers lower quality and serves a smaller share of the market, yielding approximately half the socially-efficient level of surplus.[37] The avowed intention of rate of return regulation was to help correct this inefficiency. Unfortunately, regulation is costly and introduces its own distortions.

The divestiture of AT&T was intended to improve total surplus by encouraging competition in the long distance markets. The initial effects of divestiture are captured by a comparison of the first case with the case of bilateral monopolists (Section 3.2). Compared to an integrated monopolist, marginal increases in quality have a bigger impact on price. As a result, firms choose lower quality levels, serve a smaller portion of the market, and realize lower profits despite the higher prices. Consumer surplus is lower also, implying that in this model, divestiture reduces total welfare and has a negative impact on service quality.

At the time of divesture, AT&T no longer had a monopoly over long distance service. Indeed, the emergence of alternative interexchange carriers such as MCI in the 1970s helped provide the impetus to force the divestiture of long distance and local exchange services. The case of three firms discussed in Section 3.2 captures the impact of combining divestiture with increased competition in one of the service markets. If price discrimination is permitted,

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[37] From Table 4, total surplus under a vertically integrated monopolist is 0.063, which is 59% of the socially efficient level of 0.106 (if we are constrained to uniform pricing) and 50% of the overall efficient level of 0.125 (if perfect discrimination is feasible).

competition offers an improvement relative to bilateral monopoly, but still falls short of the original vertically integrated monopoly outcome.[38]

If price discrimination is prohibited, an equilibrium with three firms is not sustainable. Two of the firms act to foreclose the third firm. If price discrimination is allowed, however, the firm which controls the bottleneck facility (i.e., the local exchange carrier in the present discussion), finds it advantageous to price so as to encourage entry of another downstream firm. This result suggests that ONA pricing by the local exchange carrier, in the absence of price regulations, would reduce total efficiency. It highlights the close linkage between price discrimination requirements, compatibility standards, quality choices, and the vertical structure of firms in the industry.

Prior to divestiture, AT&T faced competition from non-integrated long distance carriers such as MCI. MCI originally competed against AT&T with a lower quality network and had to sue AT&T for access to its local exchange services.[39] MCI won its suit. The analysis of the case discussed in Section 3.3.1 shows that competition by a lower quality, non-integrated carrier is not sustainable regardless of whether interconnection (compatibility) is required or whether price discrimination is prohibited (i.e., AT&T was required to price as a common carrier).

Today, the local exchange carriers are agitating for regulatory reforms which would permit the re-integration of local and long distance services.[40] As long as they maintain an effective monopoly over local access services, it may be necessary to regulate access pricing if non-integrated competitors are to survive.

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[38] From Figure #3, Firm #1's profits increase from 0.01235, under the bilateral monopoly solution, to 0.0244 (Section 3.4 with discrimination).

[39] MCI's network was initially smaller and its access connections were of lower quality than those of AT&T.

[40] The separation of local and long distance services is required by the Modified Final Judgement which is the consent decree between AT&T and the Justice Department governing the divestiture terms.

The second case of non-integrated competition (Section 3.3.2) involves an integrated firm with both a high quality bottleneck and a low quality sub-network competing against a non-integrated high quality firm. Here, competition is sustainable only if price discrimination is prohibited, but the outcome is worse than under the monopoly case (i.e., the solution defaults to the bilateral monopoly result). Such a situation might arise if a long distance company attempted to enter local access competition via an alliance with a cable company, an alternative access provider such as Teleport or MFS, or via cellular access (e.g., McCaw and AT&T). At least initially, we might expect the extent of facilities and the coordination of interconnection to result in the Bell Operating Company being perceived as offering higher quality access facilities.

The results considered above assume the existence of a bottleneck facility. What happens if there are two integrated firms competing as quality-differentiated duopolists? For example, imagine the situation where AT&T integrated forward into local exchange services via cellular or cable TV access while the local exchange carrier simultaneously integrated backward into long distance services. The alliances between Bell-Atlantic and TCI, Time Warner and US West, MCI and Teleport, AT&T and McCaw Cellular, etc. suggest that this may be the mode of competition in the future. Fortuitously, the results presented in Section 3.2.1 indicate that this will produce an outcome which out-performs the integrated monopolist. It is noteworthy that this is the ***only*** industry structure which out-performs the original pre-divestiture model and that even this solution falls far short of the socially optimal level of total surplus (i.e., total surplus with integrated duopolists is 0.069 versus 0.1055). Thus, even with duopoly competition in every market, continued regulation may be justified. Moreover, our results assume that the production costs are such that duopoly competition is sustainable (i.e., local access is not a natural monopoly).

Our model indicates that there are no gains from offering hybrid systems. The integrated firms will price so as to foreclose these markets. This may be unfortunate since other reasons to interconnect might exist. For example, active hybrid system markets may be useful in helping to assure network reliability (i.e., hybrid systems offer alternative routing options in the event one of the sub-networks fails). However, since real networks are unlikely to perfectly overlap the opportunity to reach additional customers will help encourage interconnection.

5. Concluding Remarks

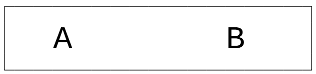
Although the preceding discussion attempted to interpret our analytic results in terms of policy questions which are of interest to telecommunications regulators, we should not forget that this is an abstract model. Its real contribution may be in expanding our understanding of the theoretical tools which underlie economic-based policy analysis. We were somewhat surprised to find that the standard models were inadequate for addressing the questions posed by the evolution towards a more highly decentralized information infrastructure.

Much work needs to be done if we are to understand the effects of changing industry structure on incentives to invest in quality. For example, two important theoretical extensions to the present work include (1) accounting for the effect of positive externalities on quality investments, and (2) incorporating imperfect, asymmetric information. In addition to these theoretical extensions, we need additional empirical work which addresses how the quality of our infrastructure has changed since divestiture.

FIGURE 1: Industry Structure Cases

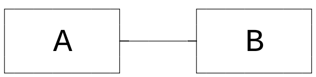
(Numbers identify firm, letter identifies component)

Section 3.1 Vertically Integrated Monopolist

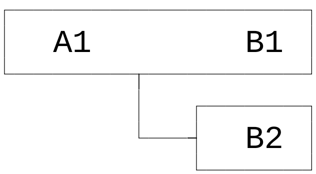


3.1.1 Single product vertically integrated monopolist
3.1.2 Multiproduct vertically integrated monopolist

Section 3.2 Bilateral Monopoly: Independent (Non-Integrated) Monopolists Upstream and Downstream

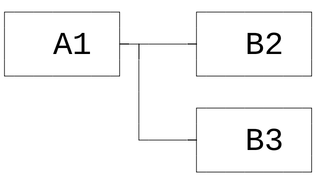


Section 3.3 Duopoly: Integrated Firm Facing Competition in One Component

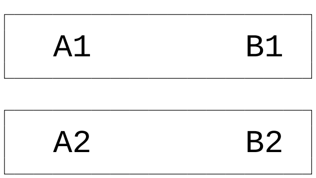


3.3.1 High quality integrated firm facing a low quality competitor in one component
3.3.2 Mixed quality integrated firm facing a high quality competitor in one component

Section 3.4 Three Independent Firms, Each Producing a Single Component. High Quality Upstream and High or Low Quality Downstream



Section 3.5 Duopoly Competition Between Two Vertically Integrated Firms

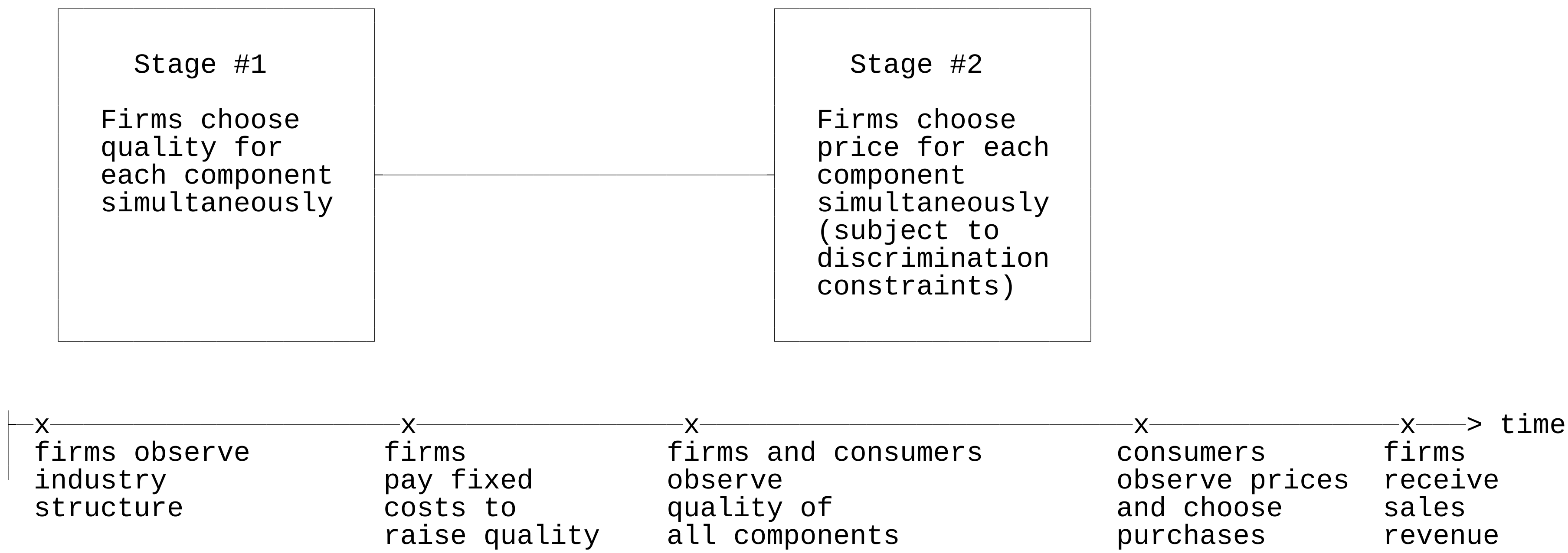


3.5.1 Duopoly Competition of Vertically Integrated Firms With Incompatible Components
3.5.2 Duopoly Competition of Vertically Integrated Firms That Produce Compatible Components

FIGURE 2: Structure of the Quality-Price Game

In each case an industry structure is defined by

- the number of firms (1, 2 or 3)
- the vertical market structure (each firm produces component A, B or both)
- whether price discrimination is allowed (different prices for components and bundles allowed?)
- whether components are compatible (are hybrid systems feasible?)



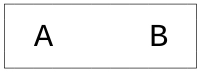
Game assumes:

- Perfect information
- Consumers distributed uniformly on unit interval, $\theta \in [0, 1]$ with $U_\theta(p, q) = \theta q - p$ if purchase; $= 0$ otherwise. p is price of product; q is quality of product $= \min(q_A, q_B)$.
- Costs of quality improvement $= \frac{1}{4} q_i^2$ where q_i is the quality of component $i = A$ or B.

FIGURE 3: Summary of Results for Industry Structure Cases

(Equilibrium values: p_i price; q_i quality; s_i market coverage; Π_i profits; CS consumer surplus)

Section 3.1



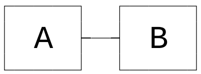
Vertically Integrated Monopolist

$p_{AB} = 0.1250$ $q_{AB} = 0.25$ $s_{AB} = 0.500$ $\Pi_1 = 0.03125$ CS = 0.03125

- Monopolist prefers not to offer a second component of either type
- Socially optimal solution with single product, uniform pricing

$p_{AB} = 0.094$ $q_{AB} = 0.375$ $s_{AB} = 0.75$ $\Pi_1 = 0.0$ CS = 0.1055

Section 3.2

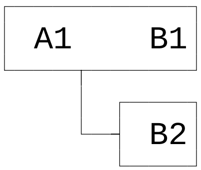


Bilateral Monopoly: Independent (Non-Integrated) Monopolists Upstream and Downstream

$p_A = p_B = 0.0741$ $q_A = q_B = 0.222$ $s_{AB} = 0.333$ $\Pi_A = \Pi_B = 0.01235$ CS = 0.01235

$p_{AB} = 0.1481$ $\Pi_{A+B} = 0.0247$

Section 3.3



Duopoly: Integrated Firm Facing Competition in One Component

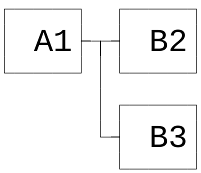
3.3.1 Integrated high quality (firm 1) vs. non-integrated low quality (firm 2)

- Firm 1 prices A_1 to foreclose firm 2 from market, and acts as monopolist

3.3.2 Mixed quality integrated (firm 1) vs. high quality non-integrated (firm 2)

- Without price discrimination, firm 1 sets $q_{B1} = 0$ and firms behave as bilateral monopolists (Section 3.2)
- With price discrimination allowed, there is no equilibrium

Section 3.4



Three firms: High Quality Upstream and High (Firm 2)/Low (Firm 3) Quality Downstream

- Without price discrimination, firm 1 and firm 2 foreclose firm 3 from market, and act as bilateral monopolists (Section 3.2).

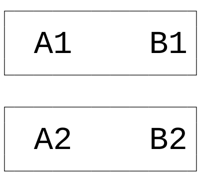
- With price discrimination allowed,

$p_{A1B2} = 0.1448$ $q_{A1} = q_{B2} = 0.222$ $s_{A1B2} = 0.337$ $\Pi_1 = 0.01471$ $\Pi_2 = 0.01050$ CS = 0.0136

$p_{A1B3} = 0.0114$ $q_{B3} = 0.0209$ $s_{A1B3} = 0.112$ $\Pi_3 = 0.00013$

$s_{A1B2} + s_{A1B3} = 0.449$ $\Pi_1 + \Pi_2 + \Pi_3 = 0.02534$

Section 3.5



Duopoly Competition Between Two Vertically Integrated Firms

3.5.1 Duopoly, both integrated firms with incompatible components

$p_{A1B1} = 0.1077$ $q_{A1} = q_{B1} = 0.253$ $s_{A1B1} = 0.525$ $\Pi_1 = 0.0244$ CS = 0.0431

$p_{A2B2} = 0.0103$ $q_{A2} = q_{B2} = 0.048$ $s_{A2B2} = 0.262$ $\Pi_2 = 0.0015$

$s_{A1B1} + s_{A2B2} = 0.787$ $\Pi_1 + \Pi_2 = 0.0259$

3.5.2 Duopoly, both integrated firms with compatible components

- Firms price so as to foreclose hybrid markets and hence solution defaults to duopoly with incompatible components (Section 3.5.1)

FIGURE 4: Summary of Results

	--- High ---		--- Low ---	
	Price	Quality	Price	Quality
Social optimum with perfect price discrimination	n/a	0.500	n/a	n/a
"" uniform pricing	0.094	0.375	n/a	n/a
Vertically integrated monopoly	0.125	0.250	n/a	n/a
Bilateral Monopoly: non-integrated upstream/downstream	0.148	0.222	n/a	n/a
Three non-integrated (w/price discrimination)	0.145	0.222	0.011	0.021
Duopoly, vertically integrated, not compatible	0.108	0.253	0.010	0.048

	Profits	Consumer Surplus	Total Surplus	Market Coverage
Social optimum with perfect price discrimination	n/a	n/a	0.125	100%
"" uniform pricing	0.000	0.106	0.106	75%
Vertically integrated monopoly	0.031	0.031	0.063	53%
Bilateral Monopoly: non-integrated upstream/downstream	0.025	0.012	0.037	36%
Three non-integrated (w/price discrimination)	0.025	0.014	0.039	36%
Duopoly, vertically integrated, not compatible	0.026	0.043	0.069	65%

Note: Industry structures which are not shown do not have equilibrium solutions and default to one of the outcomes above. For example, the case of three firms without price discrimination defaults to the case of bilateral monopoly, and the case of a non-integrated firm competing against a vertically integrated firm defaults either to the bilateral monopoly case or the vertically integrated monopoly case.

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